NUCLEAR REACTOR -THERMIONIC SPACE POWER SYSTEMS*

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ABSTRACT

The application of thermionic conversion to reactor space power systems has been investigated at power levels up to 1 eMw. The thermionic cells which hold the most promise for reactor applications employ a UC-ZrC cathode, a refractory metal anode, such as Mo, and cesium for the plasma material. The simplest reactor-cell arrangement, that with the thermionic cells on the surface (waste heat rejection directly to space from anode), offers some potential advantage in simplicity and in weight at power levels below 30 ekw when compared to rankine systems. Incorporation of the cell internal to the reactor and using a liquid metal coolant to transfer the waste heat to an external radiator allows designs of thermionic reactor systems to offer significant advantages in weight and simplicity over comparable rankine cycles, particularly at power levels above a hundred kilowatts. Specific weights as low as 4 to 5 lbs/ekw at the 300 ekw power level are indicated from preliminary system designs.

THERMIONIC CONSIDERATIONS

Experimental data which have been obtained from operation of thermionic power conversion devices are available for preliminary evaluations to be made of nuclear reactor-thermionic systems. The results of the experimental work to date have been encouraging, but sufficient data, in particular that of high temperature anode operation and that of long-life cathode operation, have not yet been obtained to determine conclusively thermionic cell performance. However, estimates of the cell performance can be made from the experiments conducted so far.

*Paper presented in part at American Rocket Society Space Power Systems Conference, Santa Monica, Calif., Sept. 27-30, 1960.

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THERMIONIC CONSIDERATIONS (Cont.)

(1) (2) (3)

From experiments on the cathodes of ZrC-UC cathodes the work function of the cathode can be calculated from a data fit to the Richardson equation; at a temperature of 3300°F the work function (ϕ_K) is 3.3 volts. The work function of the anode (ϕ_A) of a refractory metal with a few monolayers of cesium residing on the surface has been experimentally determined to be essentially that of the cesium itself when the anode is operated below 1900°F and at cesium vapor pressures in excess of 0.1 mm Hg, $\phi_A = 1.8$ volts.

For the thermal losses we will pessimistically use the cathode radiative emissivity as unity, $\epsilon_K = 1$. For the emissivity of the anode, measured values of refractory metals at 1900°F can be used, $\epsilon_A = 0.2$. This gives an effective emissivity of 0.2.

With a cathode operating temperature of 3300°F the measured electron current density from ZrC-UC is, $J_K = 8$ amp/cm^2. If the output voltage is set equal to the contact potential ($\phi_K - \phi_A$), assuming this to be the maxium power output point, the output voltage is $V = \phi_K - \phi_A = 1.5$ volts. This output characteristic voltage can only be obtained provided the cathode-anode spacing is correctly gauged to the selected cesium pressure in order that the total plasma current resistance be small.

Then, from the above an output power density can be calculated

$$P = 8 \times 1.5 = 12 \text{ watts/cm}^2.$$

The energy input to the cell can be calculated; first the radiative power loss at 3300°F is

$$P = \epsilon_{eff} \, \sigma \, T^4 = 20 \text{ watts/cm}^2 \text{ (radiation loss).}$$

The Peltier cooling power is

$$P = 8 \text{ amps} \times 3.3 \text{ volts} = 26 \text{ watts/cm (Peltier)}$$

Smaller losses are the heat loss from the cathode support stem (estimated at 10% the output) and conductive loss (estimated from Rubidum gas conduction data).

$$P = 1.2 \text{ watts/cm}^2 \text{ (stem conduction loss)}$$

$$P = 1.5 \text{ watts/cm (gas conductive loss)}$$

The expected efficiency can then be calculated

$$\eta = 12/49 = 24\%$$

obtained in a laboratory device, but not that which could be obtained in a large system. However, a 15% cell efficiency is a practical design objective with a considerable allowance made for more ideal electrical and thermal performance.

The highest efficiency which has been obtained to date with a ZrC-UC cathode cell was achieved during a test[4] at General Atomic where 10% was measured. This efficiency was achieved with a voltage of 1.5 volts and with a power density of 12.5 watts/cm^2.

An estimate can be made of the maximum anode operating temperature when an anode with the low work function of 1.8 volts is used. The limiting factor to the anode temperature is that cell performance would be substantially impaired if the back current (anode emission J_A), is greater than 10% of the forward (cathode) current. With the 1.8 volt work function an anode current of 0.8 amp/cm^2 would be obtained at an anode temperature of 1700°F. For anode temperatures above this point, the advantages of lowering the radiator weights would have to be carefully evaluated by the offsetting impairment of cell output with increasing anode temperature.

POTENTIAL SYSTEM ADVANTAGES

The reasons for investigating thermionic space power systems are based on three inherent potential advantages of thermionic conversion: (1) Increased system redundency by use of many thermionic cells as compared with single pieces of rotating machinery in rankine cycles (turbine, generator, etc.), (2) decreased complexity through the elimination of need of phase change in the coolant, and (3) lower radiator areas and weights through higher heat rejection (radiator) temperatures. The former two items can only be considered qualitatively until a system has been designed in detail. The latter can be explained in light of practical metallurgical considerations.

In the case of proposed high temperature liquid metal coolant systems for rankine and thermionic cycles, the maximum cycle temperature will be set by a materials limit, that temperature at which long-life reliability can be expected from liquid metal loops. Hence, the maximum coolant temperature at which either rankine or thermionic systems operate would be about the same. A rankine cycle must suffer a temperature drop from the maximum value across the turbine to a lower value at which the heat is rejected, approximately isothermally from the system. With a single loop vapor cycle, the approximate minimum radiator area is derived when the radiator temperature is 0.75 times the maximum cycle temperature (on the order of 500°F).(5). A double loop system would add another 100 to 200°F drop.

The thermionic cell, however, must be considered somewhat different thermodynamically than the vapor cycle heat engine. Figure 1 illustrates the comparative difference of temperatures in the two cycles. As can be observed the minimum cycle temperature for the thermionic cycle can be the anode temperature, i.e., that temperature at which the heat is rejected from the reactor. Accordingly the thermionic system can be expected to reject its waste heat at a temperature of 500 to 700°F higher than a rankine cycle. This would reduce the radiator area and hence weight by a factor of 4 to 5.

THERMIONIC CELLS EXTERNAL TO REACTOR

Thermionic cells may be incorporated into reactor systems in two general ways: 1) by wrapping the cells about the outer surface of the reactor core (to effect a configuration in which the reactor surface heats the cell cathode and waste heat is rejected directly by radiation from the cell anode), and 2) by placing the cells inside the reactor (in this arrangement a coolant loop is used to transfer the waste heat from the cell anode to an external radiator for rejection).

Obvious advantages -- an absence of moving parts and of a flowing coolant -- are to be gained by using the cells on the exterior of a reactor. However, a serious limitation is inherent with this arrangement. The specific weight of the total system can be expected to increase with increasing power level, since the surface area (i.e., the cell area or power-output area) of the reactor will increase roughly as a square of the radius, whereas the volume or weight will increase as the cube of the radius. Accordingly, the system will be most attractive at low power levels and will enjoy but limited growth potential to high power levels.

The major factor in determining the performance of the external cell system is the energy balance of a unit surface area of cell. With the collector radiating directly into space, a balance must be obtained between the total power produced and the electrical power generated, the waste heat radiated, and the temperature of radiation. The cell efficiency determines the ratio of electrical energy to radiated energy. The power produced per unit area multiplied by one minus the efficiency determines the energy to be radiated, which in turn dictates the temperature since the area is fixed for a particular system design.

Specific weights which can be expected for the external thermionic cell reactor arrangement for various power generations of the cell can be seen in Figure 2. For power generation of 10 watts/cm^2(well within that which has been demonstrated in the laboratory) specific weights of 8 to 10 lb/ekw (for the reactor and thermionic cells) could be expected as possible. This would appear to be quite competitive with rotating equipment and other power generation systems. However, Figure 3 shows the anode radiative temperature and cell efficiencies which must be expected: for 10% efficiency a radiative temperature of 3100°F is required; for 20% efficiency, a temperature of 2500°F. These temperatures are higher than any demonstrated in the laboratory to date, and probably are too high for practical thermionic cell generation.

For space power systems at the relatively low power levels of a few kilowatts to a few tens of kilowatts, where specific weights from 20 to 100 lb/ekw are typical,[6] the external cell system appears to offer some advantages. For example, at 10 ekw, with a heat rejection temperature of 2000°F and an over-all efficiency of 15%, specific weights of about 20 to 30 lb/ekw may be expected. In this power range the weight should be less than that of systems using rotating-equipment cycles. Advantages to be gained in the low-kilowatt range are: low weight, increased reliability resulting from the elimination of a cooling system (and, accordingly, the meteoroid penetration problem), and the replacement of rotating machinery with static conversion equipment. Application to higher power levels would be seriously restricted by the rapid increases in specific weight with increasing power level.

THERMIONIC CELLS INTERNAL TO REACTOR

With the addition of a cooling system to transport the waste heat from the anode of the thermionic cell to a radiator, the cell may be incorporated within the reactor core. The radiator size and temperature can be varied over wide ranges with any given thermionic cell performance.

The major components are the reactor, the electromagnetic pump, the dc to ac conversion equipment, and the radiator.

A design study of a high-powered system (300 ekw) using this arrangement has been accomplished. The basic values for thermionic cell performance used in the study are thermionic cell efficiency of 14% and power density of 11 watts/cm^2. With these values, thermionic cells were designed and incorporated within a nuclear reactor. The resulting reactor core is approximately 11 inches high and 13 inches in diameter (plus a 2-inch-thick reflector), incorporates 546 fuel element cells, and weighs 582 pounds. Line losses, dc-to-ac conversion losses, and pump r requirements power output were included in the design considerations. The over-all system efficiency is approximately 12% when including all losses.

Lithium was used as the reactor coolant and appears to be the best choice for very high-heat-transfer systems in the range from 1600°F to 2000°F. A dc Faraday-type electromagnetic pump was used to circulate the lithium. Reactor outlet temperature is 2000°F and inlet temperature is 1800°F. The radiator area is 190 square feet (95 ft^2 using radiation from two sides and with a specific weight of 2.3 lb/sq ft) and the radiator weight is 220 lbs. The specific weight of the thermionic power system at 300 ekw with the above-listed parameters is 4.2 lb/ekw.

EFFECT OF DECREASED PERFORMANCE

With this study as the design point, rough estimates of the specific weight of the over-all system have been made with other thermionic cell performance figures. Figure 4 shows total system specific weight for various power outputs (watts/cm^2) and efficiencies, with a mean radiator radiator temperature of 1700°F.

It may be observed from Figure 4 that systems even with rather poor performance (i.e.,6% efficiency with cell outputs of 8 watts/cm^2) give promise of specific weights in the range of 7 to 8 lb/ekw. Additionally, the coolant temperature may be lowered from the 1700°F point to lower values and still achieve promising specific weights at the high power levels. For example, a radiator temperature of 1500°F with 12% over-all efficient system could yield a system with a specific weight of 6 to 7 lb/ekw. This preliminary investigation indicates that the performance of the thermionic cell may vary over a wide range in efficiency and anode temperature and still yield a thermionic power system which has low specific weights.

SUMMARY

If sufficient cell operation life can be demonstrated, a space power system with specific weights of 5 to 8 lb/ekw at the 300 ekw level may be possible. Although cathode life for a year has not been demonstrated in the temperature range required for adequate cathode performance, it is quite encouraging that the power densities currently obtainable are more than adequate for low-specific-weight power systems. When compared to high-performance rubidium Rankine cycle systems (indicated in Figure 1), the thermionic space power system may be considered one of the major promising power systems for the production of electrical power in space in the future.

ACKNOWLEDGMENTS

The authors wish to acknowledge the original work on the 300-ekw thermionic space power system design by R.C.Howard, J.B. Roes, and R. J. Campana.

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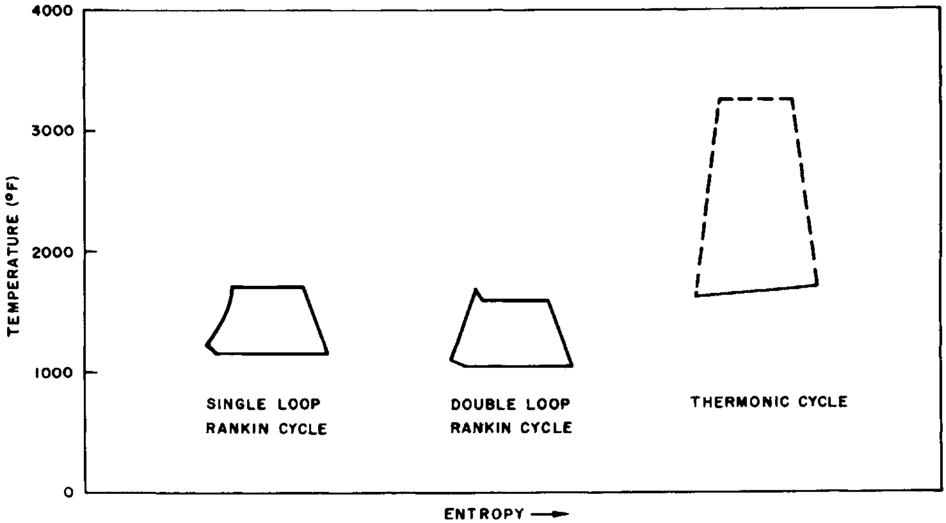

Fig. 1 Cycle Comparisons

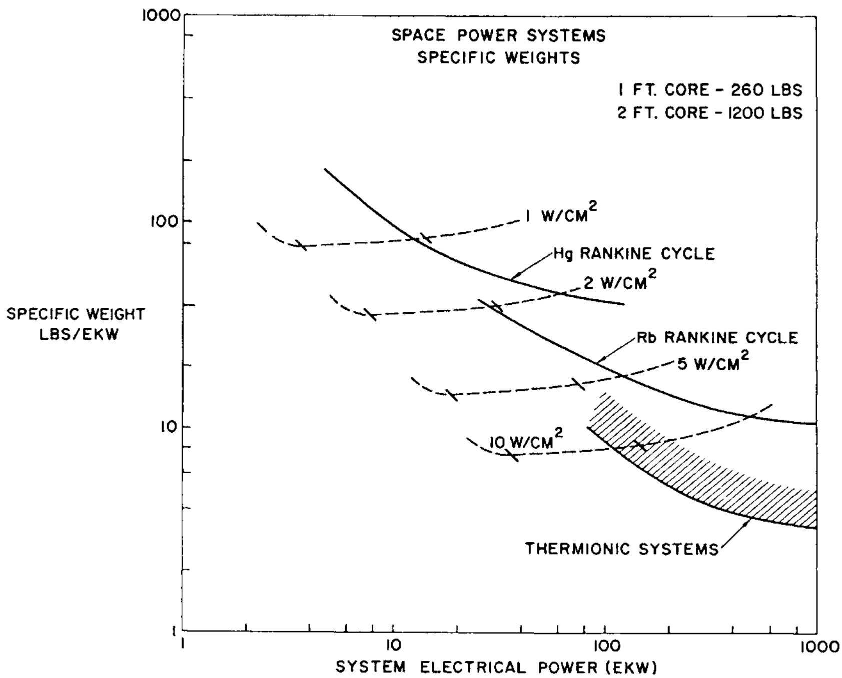

Fig. 2 Space Power Systems Specific Weights

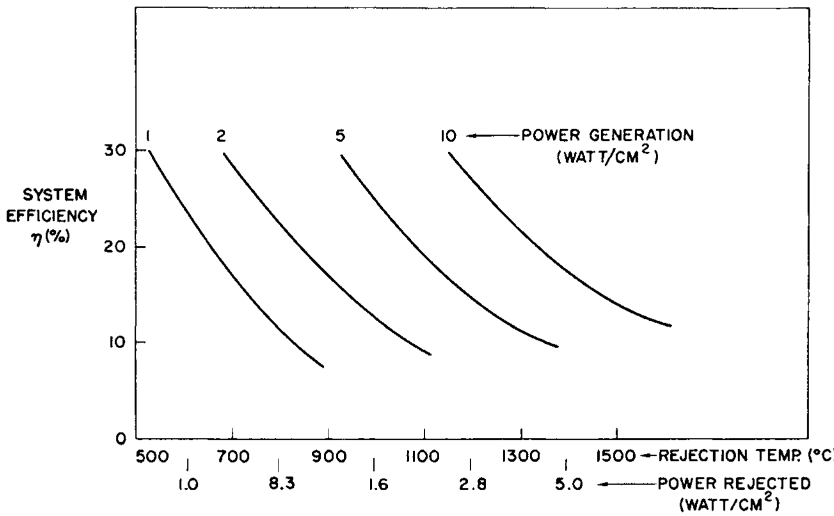

Fig. 3 Radiation Heat Rejection

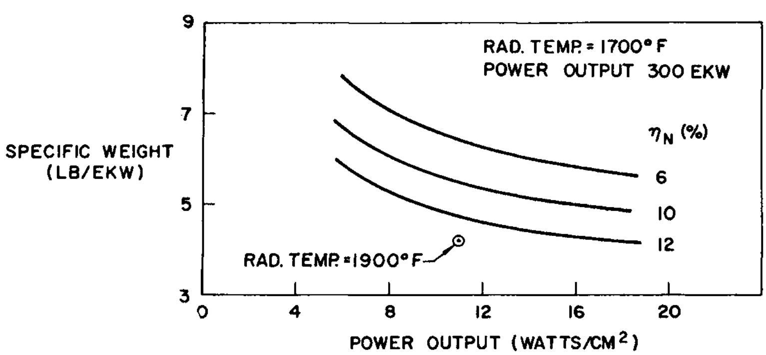

Fig. 4 Effect of P and η on Specific Weight